High-Energy Nuclear Collisions and the QCD Phase Structure

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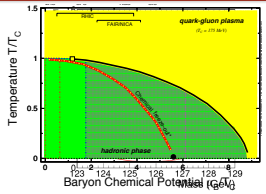
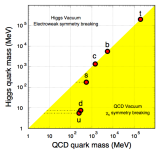
QCD in the Twenty-First Century

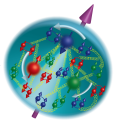


Emergent properties with QCD degrees of freedom!

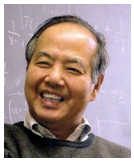
(1) Higgs (-like) Particle –
- **Origin of Mass, QCD dof**
- Standard Model ➔ The *Theory*

(2) QCD Emerging Properties –
- Confinement, χ_c symmetry
- QCD Phase Structure
- Nucleon helicity structure
- …
- Non-linear QCD at small-x
- …





How to Address the Problem?



T.D. Lee

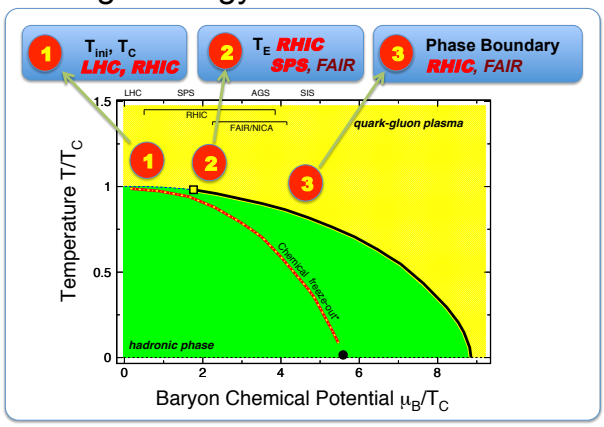
- The confinement:
  Quarks are the basic building blocks of matter.
  No free quarks are seen, confined within hadron:
  $\Delta v_0 \sim 1\ fm^3$, $\rho_0 \sim 0.16\ fm^{-3}$, $\varepsilon_0 \sim 0.15\ GeV/fm^3$

- **Heavy Ion Collisions**: Large, hot/dense system
  $\Delta v \sim 1000\ fm^3 = 1000\ v_0$
  $\rho >> 3\ fm^{-3} \sim 20\ \rho_0$
  $\varepsilon >> 3\ GeV/fm^3 \sim 20\ \varepsilon_0$
  $\Rightarrow$ **Quark Gluon Plasma (QGP)**

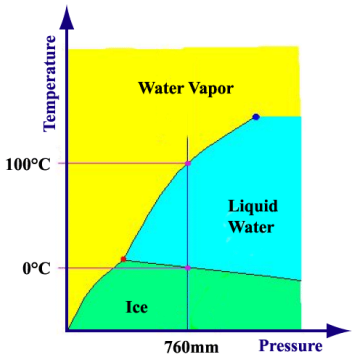
  ↗***QGP: Quarks and gluons are 'freely' moving in a large volume***
  New form of ***matter with partonic degrees of freedom***
  ↗***QCD Phase Structure***

- Connection with other fields
  cosmology, origin of the universe, evolution of the universe
  quantum statistics with partons

The QCD Phase Diagram and High-Energy Nuclear Collisions



Phase Diagram: Water



Phase diagram: A map shows that, at given degrees of freedom, how matter organize itself under external conditions.

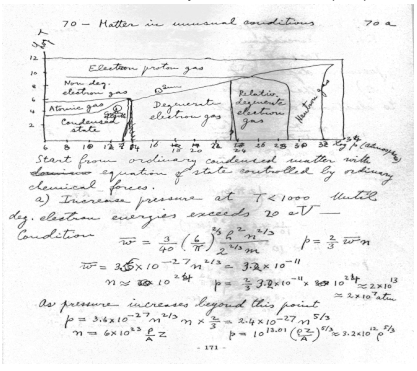
Water: H_2O

The QCD phase diagram: structure of matter with quark- and gluon-degrees (color degrees) of freedom.

QCD Phase Diagram (1953)

E. Fermi: *"Notes on Thermodynamics and Statistics "* (1953)

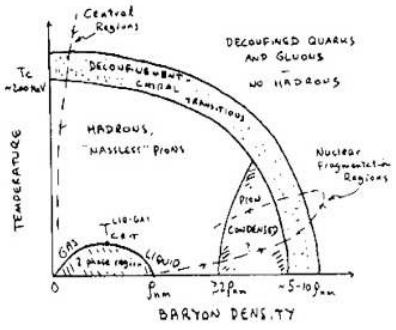
E. Fermi



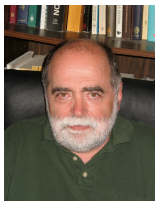
QCD Phase Diagram (1983)

1983 US Long Range Plan - *by Gordon Baym*

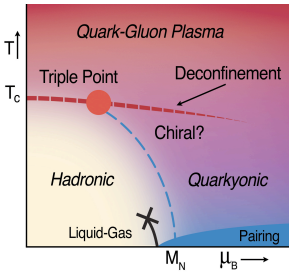
Gordon Baym



QCD Phase Diagram (2009)



Larry McLerran



nucl-th: 0907.4489, NPA830,709(09) *L. McLerran*
nucl-th 0911.4806: *A. Andronic, D. Blaschke, P. Braun-Munzinger, J. Cleymans, K. Fukushima, L.D. McLerran, H. Oeschler, R.D. Pisarski, K. Redlich, C. Sasaki, H. Satz, and J. Stachel*

Experiments: Systematic measurements (E_{beam}, A_{size}) : to extract **numbers** that are related to the ***phase diagram***!

Outline

(1) Introduction

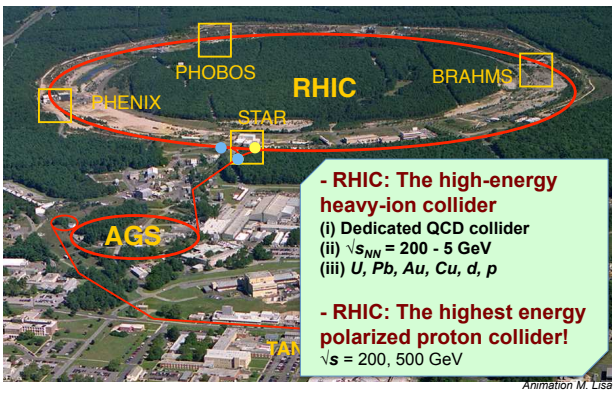
(2) Recent Results from RHIC

(3) RHIC Beam Energy Scan

(4) Summary and Outlook

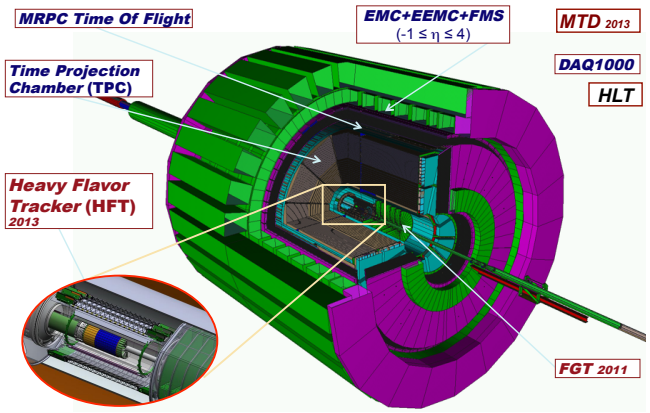
Relativistic Heavy Ion Collider

Brookhaven National Laboratory (BNL), Upton, NY

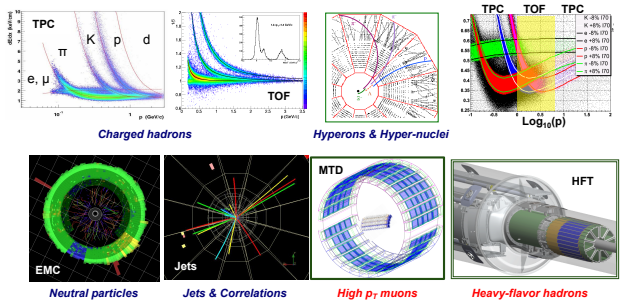


Animation M. Lisa

STAR Detector *Fast and Full azimuthal particle identification*



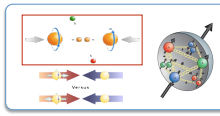
Particle Identification at STAR



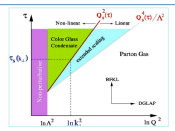
Charged hadrons | *Hyperons & Hyper-nuclei* | *Neutral particles* | *Jets & Correlations* | *High p_T muons* | *Heavy-flavor hadrons*

Multiple-fold correlations for the identified particles!

RHIC Physics Focus

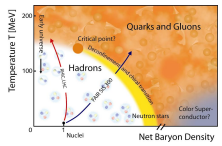


Polarized *p+p* program
- Study ***proton intrinsic properties***



Forward program
- Study low-x properties, initial condition, search for ***CGC***
- Study elastic and inelastic processes in pp2pp

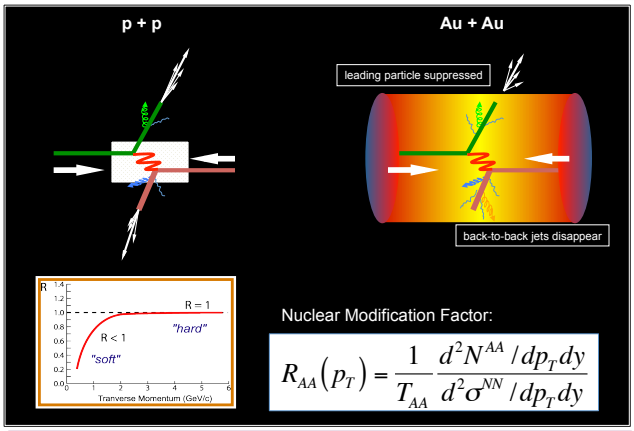
2020 -
eRHIC
(eSTAR)



1) At 200 GeV at RHIC
- Study ***medium properties, EoS***
- pQCD in hot and dense medium

2) RHIC beam energy scan (BES)
- Search for the ***QCD critical point***
- Chiral symmetry restoration

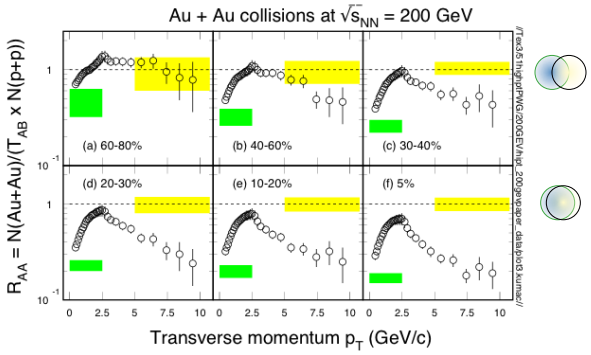
Jet Quenching at RHIC



Nuclear Modification Factor:

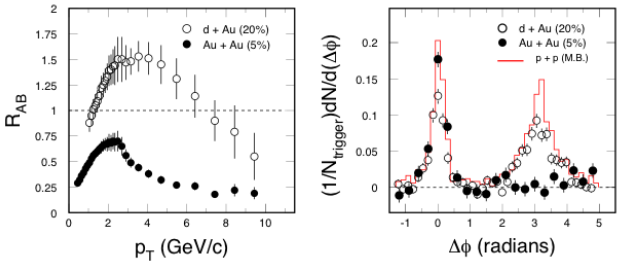
$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{d^2N^{AA}/dp_T dy}{d^2\sigma^{NN}/dp_T dy}$$

Hadron Suppression at RHIC



Hadron suppression in more central Au+Au collisions!

Suppression and Correlation

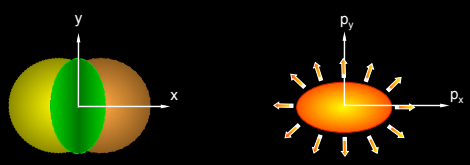


In central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV: light quark hadrons and away-side jets are suppressed.

Energy density at RHIC: ε > 5 GeV/fm^3 ~ 30ε$_0$

Anisotropy Parameter v_2

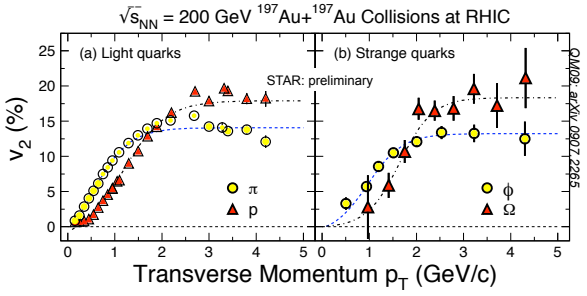
coordinate-space-anisotropy ➪ momentum-space-anisotropy



$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \ \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

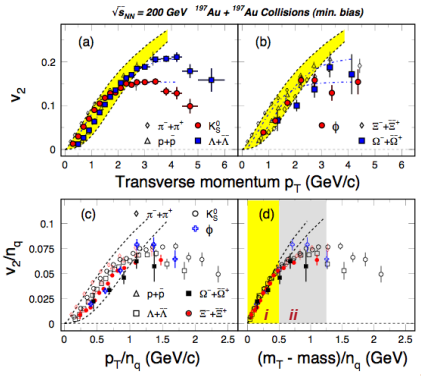
Partonic Collectivity at RHIC



Low p_T (≤ 2 GeV/c): hydrodynamic mass ordering
High p_T (> 2 GeV/c): ***number of quarks scaling***

➔ ***Partonic Collectivity, necessary for QGP!***
➔ ***De-confinement in Au+Au collisions at RHIC!***

Collectivity, Deconfinement at RHIC



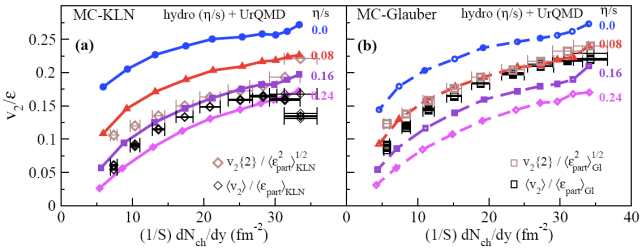
- v_2 of light hadrons and multi-strange hadrons
- scaling by the number of quarks

At RHIC:
➪ m_T - NQ scaling
➪ De-confinement

PHENIX: PRL**91**, 182301(03)
STAR: PRL**92**, 052302(04), **95**, 122301(05)
nucl-ex/0405022, QM05

S. Voloshin, NPA715, 379(03)
Models: Greco et al, PR**C68**, 034904(03)
Chen, Ko, nucl-th/0602025
Nonaka et al. **PLB583**, 73(04)
X. Dong, et al., Phys. Lett. **B597**, 328(04).
....

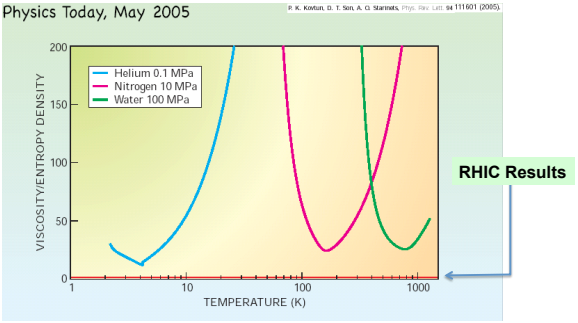
Comparison with Model Results



➔ ***Small value*** of specific viscosity over entropy ***η/s***
➔ Model uncertainty dominated by ***initial eccentricity ε***

Model: Song *et al. arXiv:1011.2783*

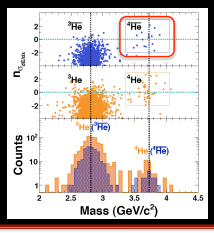
Low ***η/s*** for QCD Matter at RHIC



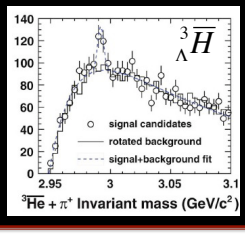
1) ***η/s ≥ 1/4π***
2) ***η/s***(QCD matter) << ***η/s***(QED matter)

Antimatter Discoveries at RHIC

nature April, 2011
"Observation of the Antimatter Helium-4 Nucleus"
by ***STAR Collaboration***
Nature*, 473, 353(2011).*

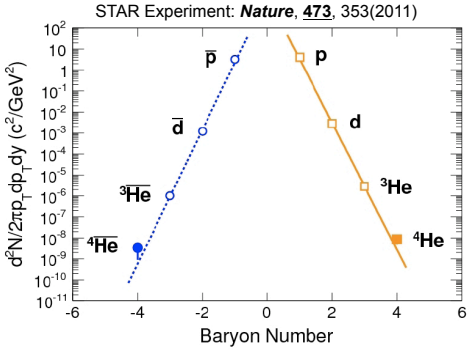


Science March, 2010
"Observation of an Antimatter Hypernucleus"
by ***STAR Collaboration***
Science*, 328, 58(2010).*



Light Nuclei Productions at RHIC

STAR Experiment: ***Nature***, **473**, 353(2011)



1) In high-energy nuclear collisions, **N(d) >> N(α)**:
QGP ➔ (anti)light nuclei via coalescence
2) In the Universe, **N(d) << N(α): N(anti-α)?**

Summary I:

sQGP formed at Au+Au Collisions at 200 GeV

(1) In high-energy nuclear collisions, hot and dense ***matter,*** with ***partonic degrees of freedom*** and **collectivity,** has been formed

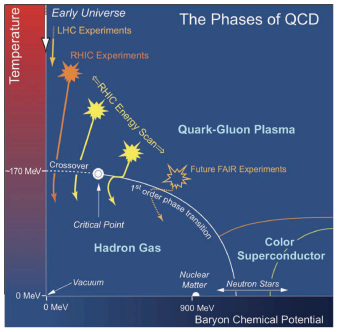
(2) The matter behavior like a ***quantum liquid*** with small ***η/s***

(3) Partonic matter ➔ **antimatter**: ${}^{3}_{\Lambda}\overline{H}$, ${}^{4}\overline{He}$

What is the structure of the QCD matter?

Beam Energy Scan (BES) at RHIC

Study QCD Phase Structure
- Signals of phase boundary
- Signals for critical point



Exp. Observations:

(1) v_2 - NCQ scaling: partonic vs. hadronic dof

(2) Dynamical correlations: partonic vs. hadronic dof

(3) Azimuthally HBT: 1st order phase transition

(4) Fluctuations: Critical point, correl. Length **net-p**, net-Q, … mixed ratios C_2, C_4, C_6, C_8, …

(5) Directed flow v_1 1st order phase transition

- http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493
- arXiv:1007.2613

Susceptibilities and Moments

Thermodynamic function:

$$\frac{p}{T^4}=\frac{1}{\pi^2}\sum_i d_i(m_i/T)^2 K_2(m_i/T)\cosh[(B_i\mu_B+S_i\mu_S+Q_i\mu_Q)/T]$$

The susceptibility: $T^{n-4}\chi_q^{(n)}=\frac{1}{T^4}\frac{\partial^n}{\partial(\mu_q/T)^n}P\left(\frac{T}{T_C},\frac{\mu_q}{T}\right)\Big|_{T/T_C}, \quad q=B,Q,S$

Conserved Quantum Number

$$\chi_q^{(1)}=\frac{1}{VT^3}\langle\delta N_q\rangle$$

$$\chi_q^{(2)}=\frac{1}{VT^3}\left\langle(\delta N_q)^2\right\rangle$$

$$\chi_q^{(3)}=\frac{1}{VT^3}\left\langle(\delta N_q)^3\right\rangle$$

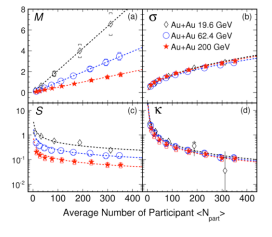
$$\chi_q^{(4)}=\frac{1}{VT^3}\left(\left\langle(\delta N_q)^4\right\rangle-3\left\langle(\delta N_q)^2\right\rangle^2\right)$$

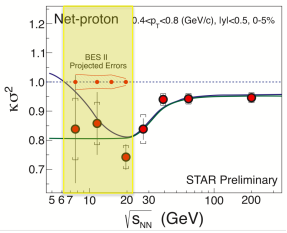
$$\frac{T^2\chi_q^{(4)}}{\chi_q^{(2)}}=\kappa\sigma^2, \qquad \frac{T\chi_q^{(3)}}{\chi_q^{(2)}}=S\sigma$$

Thermodynamic function ⇔ Susceptibility ⇔ Moments

Model calculations, *e.g.* LGT, HRG ⇔ Measurements

High Moments of Net-protons



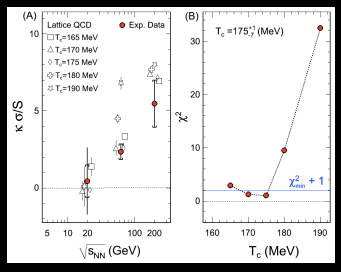


- Measure conserved quantities, ***B, s, and Q***.
- **First:** High order fluctuation results consistent with thermalization.
- **First:** Tests the *long distance QCD* predictions in hot/dense medium.

Caveats: (a) static vs. dynamic; (b) net-B vs. net-p; (c) potential effects of freeze-out…

- R. Gavai, S. Gupta, 1001. 3796 / F. Karsch, K. Redlich, 1007.2581 / M. Stephanov, 0911.1772.
- STAR: PRL105, 02232(2010) and references therein.

Scale of Hot/Dense Matter on LGT



Science AAAS June, 2011

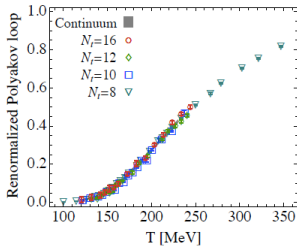
"Scale for the Phase Diagram of Quantum Chromodynamics"

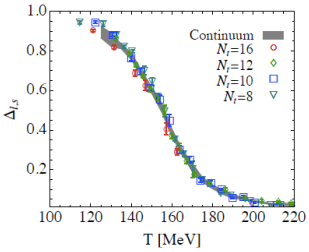
Science, 332, 1525(2011)

1) Central collisions at RHIC, the high moments measurements are consistent with thermal equilibrium assumption
2) Scale of LGT, determined with the data, is: T_C=175$^{+1}_{-7}$ (MeV)

STAR, ***PRL***105, 22303(2010); S. Gupta, X.F. Luo, B. Mohanty, H.G. Ritter, NX, ***Science***, 332, 1525(2011); F. Karsch and K. Redlich, ***PLB***695, 136(2011); R.V. Gavai and S. Gupta, ***PLB***696, 459(2011).

Lattice: Phase Transition Temperature

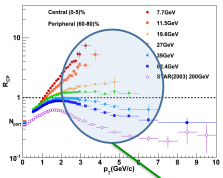




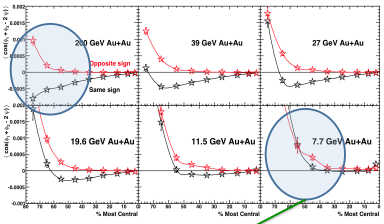
Action	Temperature
Polyakov Loop	T_C^{conf} ~ 170 MeV
Chiral Operator	T_C^{Chiral} ~ 160 MeV
RHIC Data	T_C^{Exp} ~ 175$^{+1}_{-7}$ MeV
	(T_{CH}^{Exp} ~ 160±5 MeV)

RHIC BES-I Highlights

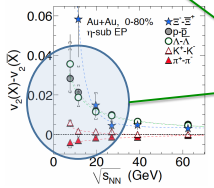
(2) Jet-quenching



(4) "Local Parity Violation"



(3) NCQ Scaling in v_2



sQGP key signatures *turned off!*

Summary II: BES-I

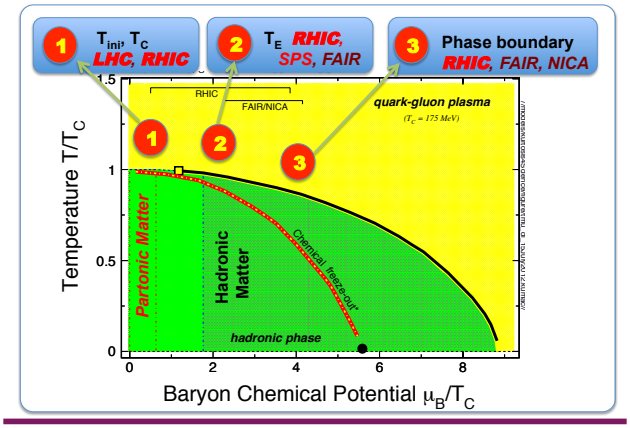
1) Partonic collectivity in 200 GeV collisions

2) At $\sqrt{s_{NN}} \leq 11.5$ GeV

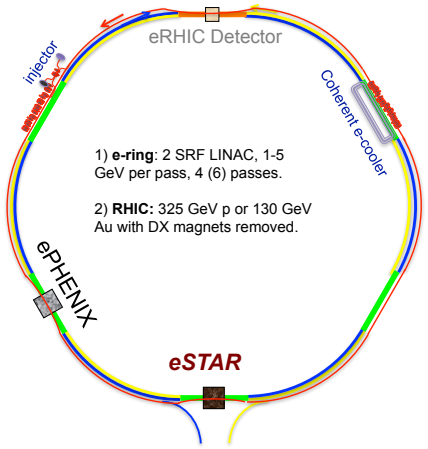
- v_2(baryon) > v_2(anti-baryon)
- $v_2(\phi) < v_2$(hadron) (2.6σ)

➔ $\sqrt{s_{NN}} \leq 11.5$ GeV: **hadronic dominant**
$\sqrt{s_{NN}} \geq 39$ GeV: **partonic dominant**

Exploring QCD Phase Structure



Outlook: eRHIC



eRHIC:
(2022-2025)

e beam: 20-30 GeV
p beam: 325 GeV
ion beam: 130 GeV
1 dedicated detector

ePHENIX/eSTAR:
(2018-2022)

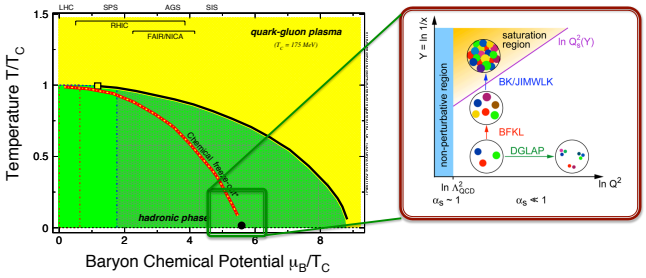
e beam: 5 GeV
p beam: 325 GeV
ion beam: 130 GeV

S. Vigdor: 2010 RHIC operational review

QCD Phase Structure

Hot QCD Matter

Cold QCD Matter



RHIC/LHC ***EIC (eRHIC)***

Summary

During the next decade and beyond, RHIC will do:

1) RHIC Top Energy (200 GeV):
Properties of the QGP: T_i, T_c, η…

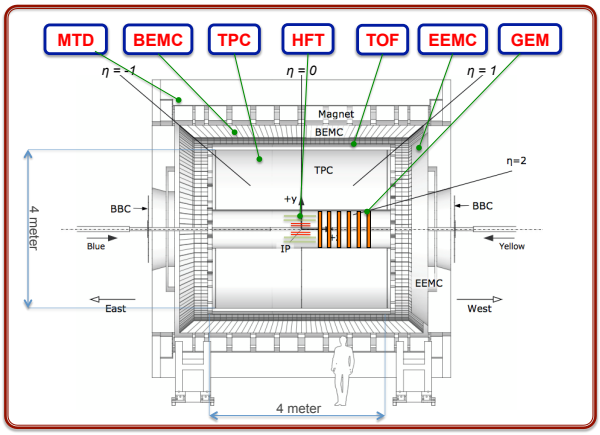
2) RHIC Beam Energy Scan (BES-II) (5-20 GeV):
QCD critical point, phase boundary

3) Polarized p+p Collisions:
Sea quark and gluon contributions to proton helicity structure

4) Future: Evolution to small-x physics: eRHIC
- Partonic structures of nucleon and nuclei, spin, 3D-imgine, ...
- Dynamical evolution from cold nuclear matter to hot QGP

Phase Structures of QCD Matter

STAR Detector System (2014)



STAR Forward Upgrade Plan (2018)